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**A topic of much debate in gallium arsenide IC manufacturing currently is the challenge to HBTs from new Enhancement-mode pHEMT transistors for power amplifiers in low-voltage, portable wireless handsets. This was reflected in a panel session at the 22nd IEEE GaAs IC Symposium in Seattle last November ("E-mode pHEMTs are killing HBTs") and, more recently, by the first E-pHEMT product launches by leading GaAs RFIC manufacturers.**

# E-pHEMT complements HBT - may challenge below 3 V

According to market research firm **Strategies Unlimited** (Mountain View, CA, USA), the HBT's share of the GaAs IC market has increased from 1998's 17% to 30% last year, almost entirely at the expense of ion-implanted MESFETs decreasing from 65% to 50%.

This is particularly due to a critical disadvantage of MESFETs and conventional Depletion-mode pHEMTs: in addition to a positive voltage supply, they also need a negative voltage supply and switch to turn off a drain leakage current of milliAmps from running down the battery during switch-off. In contrast, the HBT needs just a single positive power supply.

However, recently Enhancement-mode pHEMTs have been introduced which have drain leakage currents of just microAmps. This makes the negative voltage supply and drain switch unnecessary and enables single-supply operation.

| | "True" E-pHEMT | "Conservative" HBT | "Aggressive" HBT |
|---|---|---|---|
| **Technology** | | | |
| Front-side masks | 10 | 11-12 | 11-12 |
| MMIC die area | 1.3-1.7x | 1.1-1.3x | 1x |
| **Device** | | | |
| Device area | 7x | 1.3x | 1x* |
| Performance and repeatability | 70% epi driven | 90% epi driven | 90% epi driven |
| | 30% process driven | 10% process driven | 10% process driven |
| Reliability | No issues | Minor | More significant |
| **Application** | | | |
| Saturation-mode PAs | Best | Good | Good |
| Linear-mode PAs | Good | Best | Best |
| Low-noise amplifiers | Best | Good | Good |

** But, before adding ballasting, pads and passive devices.*

*Table 1. A comparison of true Enhancement-mode pHEMT with "conservative" and "aggressive" HBT transistor designs (Courtesy: Mark Wilson, Motorola).*

In particular, GaAs IC Symposium panel session moderator Brad Nelson of **Stanford Microdevices** notes the recent "insurgence of Enhancement-mode pHEMTs into low-voltage [battery-powered] applications", e.g. 0.5-2 V (for 2.5G and 3G telecom technology) with linearity of 12 dBm, low off-leakage, and efficiency at power.

"Single-supply power amplifiers have become the new paradigm in portable phone handsets due to the recent availability of near-zero threshold voltage pHEMT and HBT technologies", says Jim Oakland, manager of design and technology for the Wireless Transmitter Solutions Division.

"E-mode GaAs technology helps to reduce the cost and size of the end-product by eliminating both the negative voltage generator and [due to its low off-state leakage current] the drain-supply switch [needed for depletion-mode pHEMT and MESFET devices] within the handset power amplifier section, as well as eliminating additional passive components", Oakland adds.

**Motorola**'s Mark Wilson explained how they make "true" (i.e. truly off) E-mode self-aligned devices (self-alignment being "critical to get ultimate performance"). Qualified for production last November (at the CS-1 6" fab in Tempe, AZ, USA), they are available from February as a three-stage power amplifier for 1900 MHz TDMA which has delivered +30 dBm output power, 42% power-added efficiency, adjacent channel power of -30 dBc, and alternate adjacent channel power of -48 dBc (see Issue 1, page 5). Compared to "pseudo-enhancement" E-pHEMTs, which have a gate threshold (built-in) voltage of +0.8V (and therefore lower output) and a higher source-drain off-state current ($I_{DSoff}$>10 μA), Motorola's 0.8 μm gate true E-pHEMTs have a high Schottky forward gate turn-on voltage of +1.8 V (at 1 mA/mm). This allows a threshold voltage of +0.6 V, which reduces off-state leakage current - desirable for power amplifiers since it raises the output power capability of the device, while reducing the amount of gate current developed under high RF drive levels (compared to +0.8 V for a comparable depletion-mode or near-zero threshold pHEMT device). Also, $I_{DSoff}$ <100 nA (eliminating the need for a drain switch).

Motorola also says that, compared to an "aggressive" HBT process, its true E-mode pHEMT has a shorter process and cheaper epi wafers (see Table). There is a 1.3-1.7x disadvantage on MMIC die size and a 7x disadvantage on device area but - after adding an HBT's ballasting, pads and passives - total area is comparable. Also, the E-pHEMT uses only 10 front-side masks (including passives) compared to 11-12 for an HBT. Wilson reckons that the E-mode pHEMTs are 70% epi driven and only 30% process driven (compared to 90% and 10% for HBTs) and have "no reliability issues".

**Agilent Technologies Inc** has also launched an E-pHEMT power amplifier process developed at Agilent Laboratories (see Issue 6, 2000, page 8). It claims its E-pHEMT will offer higher performance than both today's GaAs HBT power amplifiers and future InGaP HBTs and improve CDMA cellphone battery life by up to 15%. Smaller batteries will allow more room for new features in multiband and 3G phones.

The first product (launched last November) is a high-dynamic-range transistor. In Q1/2001, Agilent will introduce E-pHEMT power modules into its CDMAdvantage RF chipset and amplifiers for GSM.

Of other GaAs HBT suppliers:

Gene Tkachenko of **Alpha Industries** says that the company is working on "true" E-mode pHEMTs but currently makes "quasi"-E-pHEMTs which have $I_{DSoff}$ =10 μA and need a drain switch (in contrast to the single supply voltage of HBTs and true E-pHEMTs). Tkachenko reckons that (for a dual-band GSM/DCS MMIC power amplifier) an HBT has a 10-15% smaller die than a QE-pHEMT.

For 3.2 V operation at 900 MHz, the pinch-off voltage is $V_p$=0.3 V and the gate threshold (built-in) voltage about 0.8 V (compared to about 1.8 V for Motorola's true E-PHEMT).

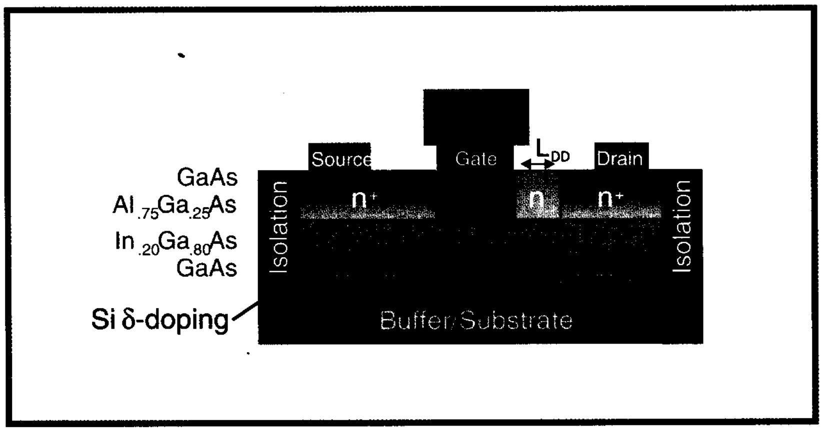


*Figure 1. Cross-sectional schematic diagram of the layer structure of Motorola's Self-Aligned Enhancement-mode HIGFET transistor.*

However, when the supply voltage drops from 3.5 V to 1 V, the ratio of Power Added Efficiency to Output Power (PAE/$P_{out}$) in a QE-pHEMT is maintained above 70%, whereas in an HBT it drops to about 53% due to a larger knee voltage. Also, though small-signal gain is typically higher for an HBT at all supply voltages, compresses earlier, again due to the larger knee voltage as the input power increases.

Other trade-offs include:
• electrical performance is dependent on process stability for E-pHEMTs and on thermal design for HBTs;
• failure mechanisms are electrically activated in E-pHEMTs and thermally activated in HBTs;
• impedance mismatch is high for E-pHEMTs and low for HBTs.

Tkachenko concludes that E-pHEMTs have an advantage for low-voltage applications and higher Power Added Efficiency, although they need a Variable Voltage Attenuator for complete shut-off at zero gate-source voltage ($V_{GS}$=0).

Dave Halchin of **RF Micro Devices** (which makes HBTs) emphasised that, in E-pHEMTs that need a drain switch, the turn off is process-dependent due to the E-pHEMT's recess etch and small layer thickness (<150-200Å, where a variation of 1Å equates to 10 mV, so a few monolayers variation can equate to 650 mV). By contrast, an HBT's epi processing needs only thick layers (> 2 μm) so its turn off is less sensitive to process variations and is dependent instead on bandgap.

Also, he says the HBTs die size of <1 mm$^2$ allows 3-5x more die per wafer (a few thousand for GSM applications).

In contrast, FETs are surface devices and not subject to dispersive effects, and are therefore more consistent from DC to RF. FETs are hence more rugged, with thermal runaway "not an issue".

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***"An HBT's epi processing needs only thick layers (of more than 2 µm) so its turn off is less sensitive to process variations and is dependent instead on bandgap"***

**Dave Halchin of RF Micro Devices**

Whereas HBTs need ballasting, a resistor divider is adequate for biasing a FET, which has no gate current and therefore no need for an active network. Noise performance is inherently better, whereas an HBT's is "adequate".

Aditya Gupta of **ANADIGICS** agrees that $V_B$ control is easier in an InGaP HBT (due its vertical current flow) than in an E-pHEMT (due to horizontal surface effects). Also, device geometry is under 1 µm. In addition, InGaP HBTs are robust. Leakage current is low (with no switch needed, and only limited by substrate isolation). He questions how much worse an E-pHEMTs leakage is at high temperature. Gupta says that their InGaP HBT has "excellent" reliability, quoting a Mean-Time-To-Failure (20% current drop) of $3 \times 10^9$ hrs at 3.3V and a junction temperature of $T_j$=125°C with an activation energy of $E_A$=1.8 eV. In contrast, Gupta questions an E-pHEMTs "power slump" due to charge trapping effects in the nitride dielectric between the gate and the drain.

Gupta adds that epi is available from many vendors for InGaP HBTs but few for E-pHEMTs.

But any consensus centres on the fact that the device type is probably not so critical for performance. As long as the device is not operated on the "knee" (of its current-voltage dependency), then performance is dependent on the back-off voltage and hence more on circuit design.

However, according to Motorola's Wilson, it is not a question of E-mode vs HBT but of applying both technologies as complementary tools: E-mode pHEMTs are best for saturation-mode power amplifiers and low-noise amplifiers; HBTs are best for linear-mode power amplifiers.

The main difference in device performance is at low voltage. Below 3V, said Wilson, an HBT's current "goes through the roof", resulting in more power loss ($I^2R$). However, it is currently difficult for cell-phone makers to go below 3V (e.g. to 2.4V) due to the lack of availability of an appropriate battery technology to replace the current 3V lithium-ion batteries. If, or when, operation of mobile wireless devices becomes feasible at voltages below 3V, then E-pHEMTs may begin to show a clear advantage over HBTs for this application.